Cherenkov and Scintillation Light Separation in Liquid Scintillators

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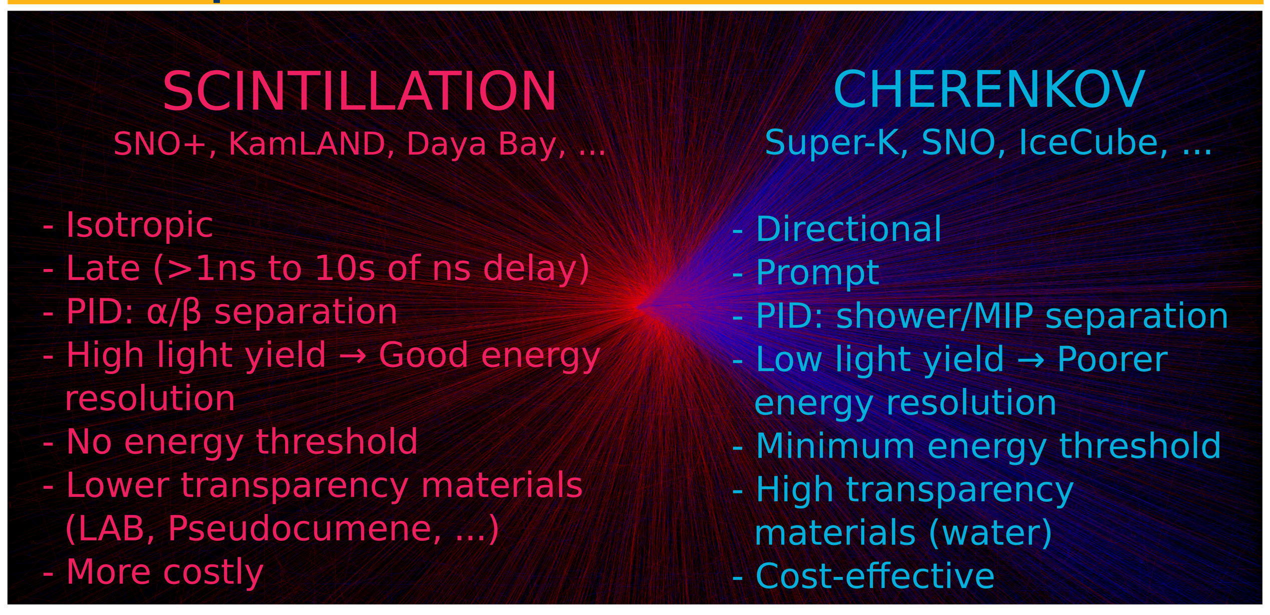
INTRODUCTION

Optical Detection Methods

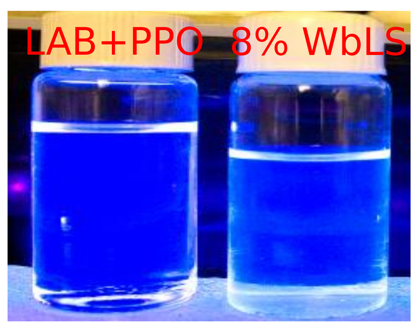


Goal
Demonstrate the separation of Cherenkov and scintillation light produced by charged particles in various LS and WbLS target media.

Motivation
Succesful signal separation would allow directional reconstruction in low-threshold detectors, with enhanced particle identification.

Method
Image a Cherenkov ring in target media using charge and time information from ultra-fast, high quantum efficiency photo-sensors.

Water-based Liquid Scintillator



Water-based Liquid Scintillator (WbLS) is a new material recently developed [1] by suspending organic liquid scintillator (e.g. Linear alkylbenzene or **LAB**) in water. The result is a novel target medium with a tunable scintillation component and good optical properties.

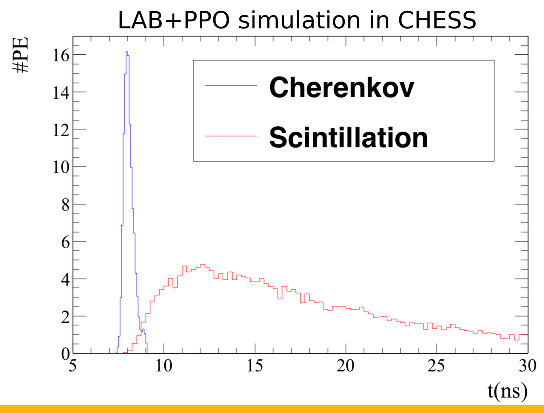
Separation in WbLS

Separation of the Cherenkov and scintillation components in liquid scintillator is theoretically possible using ultra-fast photon detectors, but has never been realized in a large detector. Separation in WbLS is substantially enhanced by tuning the scintillation light yield and timing profile. This would permit construction of large, directional, low-threshold detectors. The benefits include:

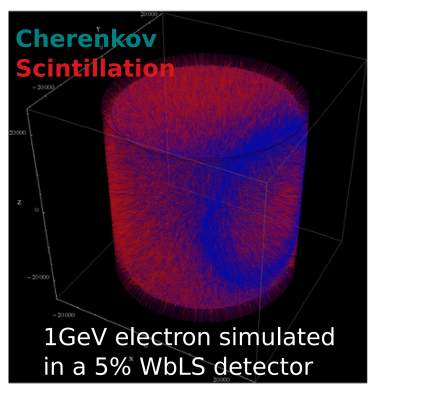
- Signal discrimination via directionality (e.g. NLDBD vs solar neutrinos)
- Low threshold scintillation detection
- Good energy resolution
- Good optical properties
- Enhanced particle ID via comparison of scintillation and Cherenkov components.

Two Separation Techniques

Photon timing
The scintillation light is typically delayed by >1ns (to 10s of ns) with respect to the Cherenkov light. The early photoelectron population is dominated by Cherenkov photons.

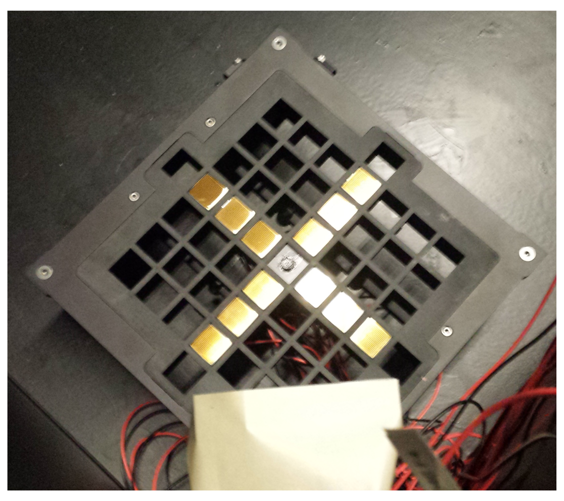


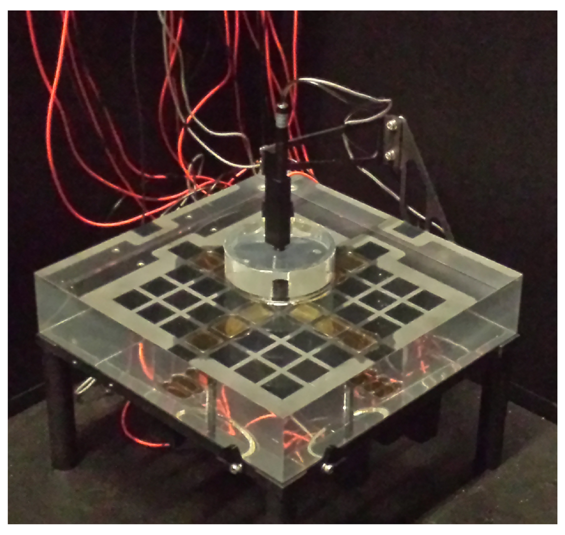
Photon density
The distinct topology of Cherenkov light in comparison to the isotropic nature of scintillation means that the characteristic Cherenkov ring structure can potentially be distinguished on top of the isotropic scintillation background using deposited charge.

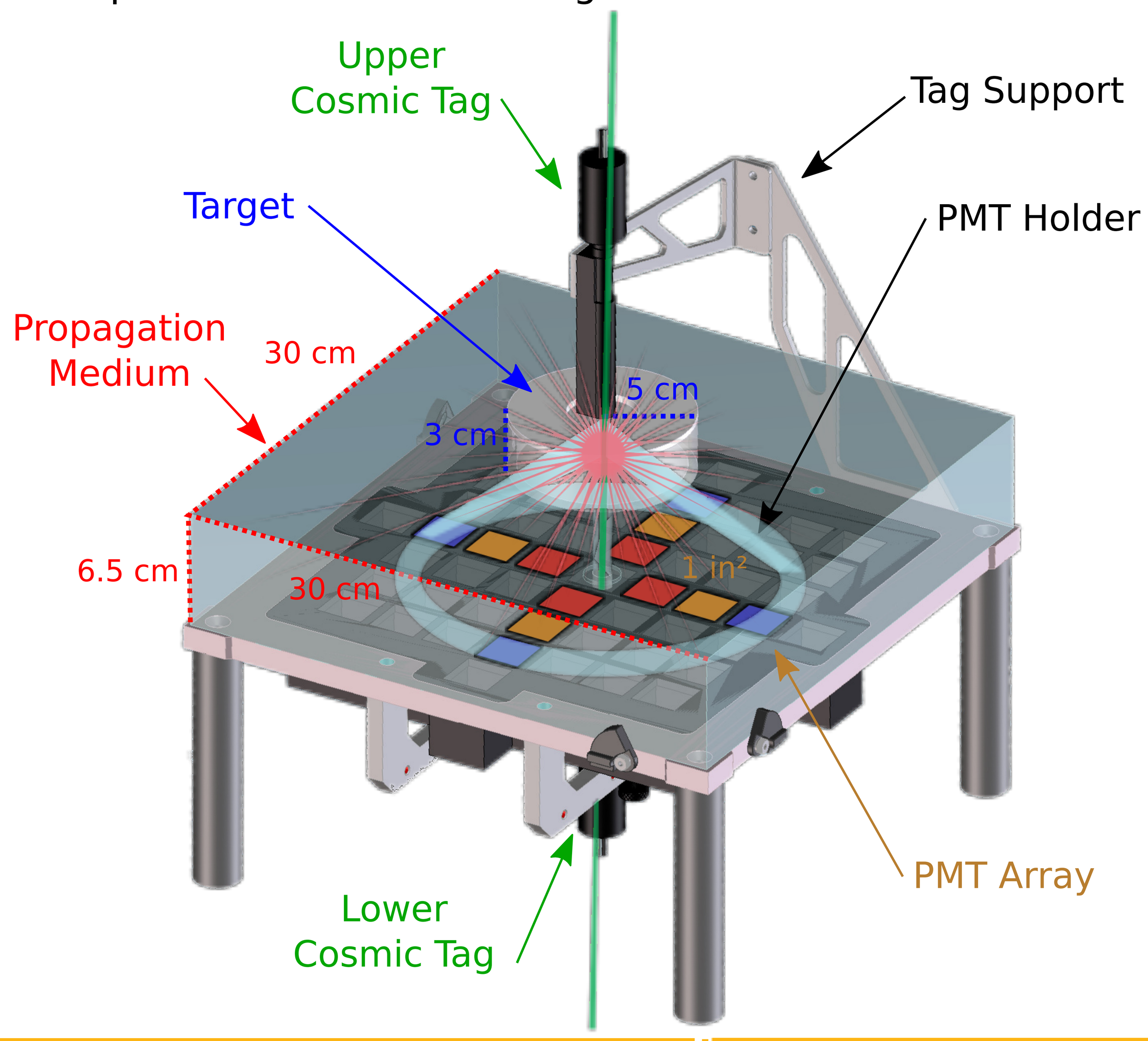


THE CHESS EXPERIMENT [5]

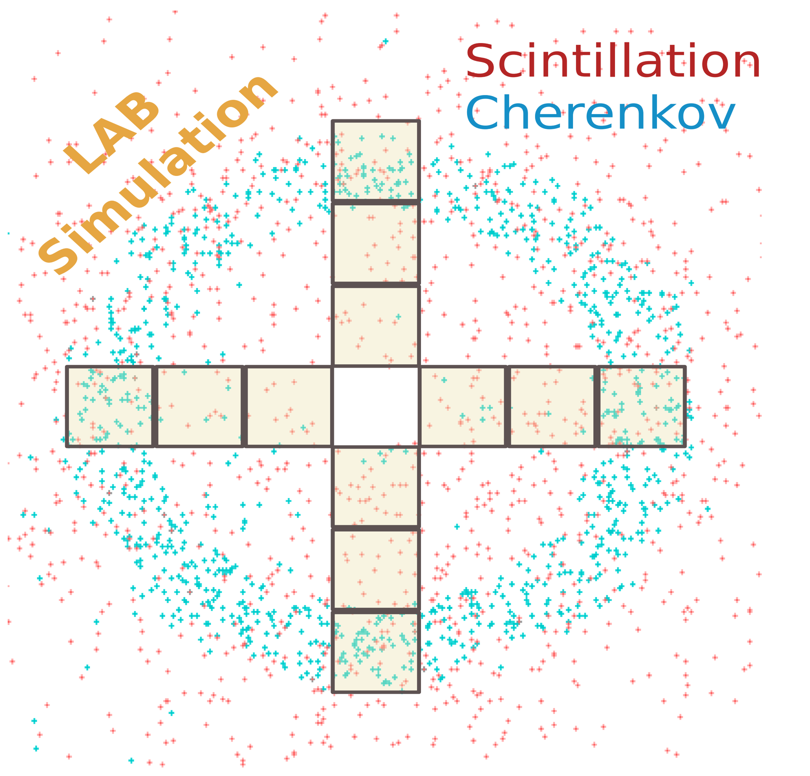
The goal of the CHESS experiment is to demonstrate the feasibility of **separating the Cherenkov and scintillation components in LS and WbLS**. The separation can be achieved using both photon timing and charge density. The apparatus can also be used for **target characterization**: to measure the light yield and time profile of the chosen target medium.







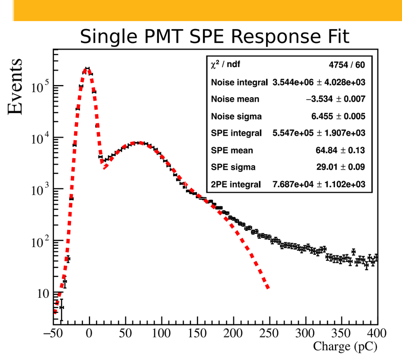
A cosmic muon that passes through the liquid scintillator target produces Cherenkov and scintillation light which propagate through an acrylic medium towards the PMT array. Two scintillator tags allow selection of vertical-going muon events. The PMT array registers both the **isotropic scintillation photons** and the **directional Cherenkov photons**. Based on the refractive index of the target material, and thus the Cherenkov angle, there will be a set of PMTs hit by **both scintillation and Cherenkov light** and a set hit by **pure scintillation** (see figure below). These can be distinguished both by **charge density** and photon **hit times**. Radioactive sources can be deployed to provide ionization by multiple particle types with known energy spectra.



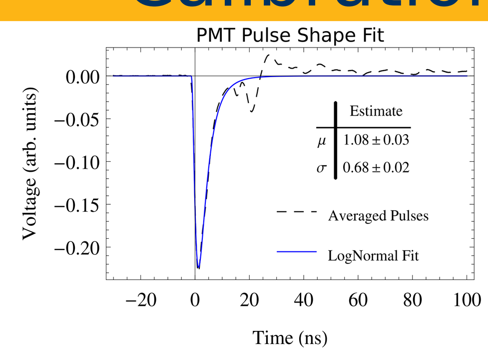
Components:

- Cross-shaped PMT array with twelve 1" Hamamatsu H11934-200, high quantum efficiency (42%), high-precision transit time spread (300ps FWHM)
- Two 1-cm diameter scintillator tags with H3164 PMTs for identifying vertical muons (6 degree acceptance)
- Four EJ-200 1m x 0.5m x 5.3cm veto panels
- CAEN V1742 digitizer (5GHz, 200ns max window, 12bit 1V dynamic range)

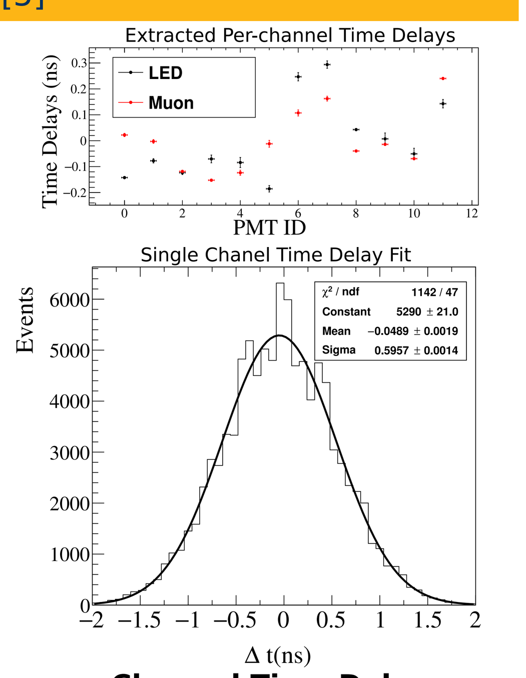
Calibration [5]



PMT Gains
Using a 90Sr button source attached to a water target dim Cherenkov light is produced to capture the single photoelectron behavior of the PMTs



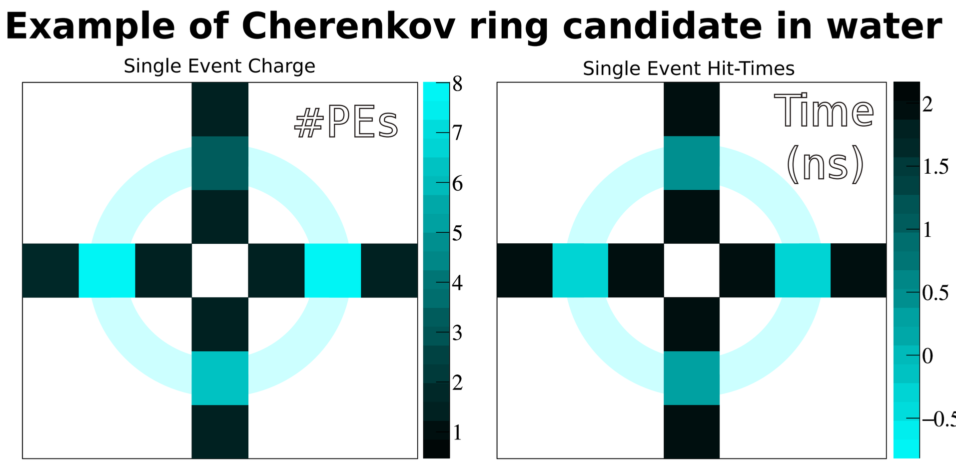
PMT Pulse Shapes
To model the time response accurately in the simulation the pulse shapes of the PMTs are fit to lognormal distributions and the resulting fit is used to simulate realistic pulses before applying per-channel fixed threshold discriminators at 25% the height of the SPE response for the channel.

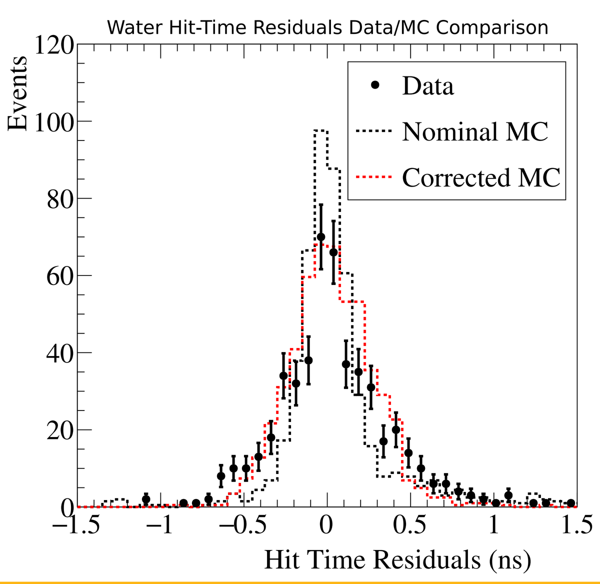


Channel Time Delays
An LED deployed on axis above the setup allows fine calibration of per-channel time delays. This was compared to time delays extracted using a control sample of cosmic muons passing through the block in order to evaluate the systematic uncertainty on this measurement.

Event Selection
Cosmic muons through a water target (left) provided a cherenkov-only sample of data to define event selection and data quality criteria.

Example of Cherenkov ring candidate in water

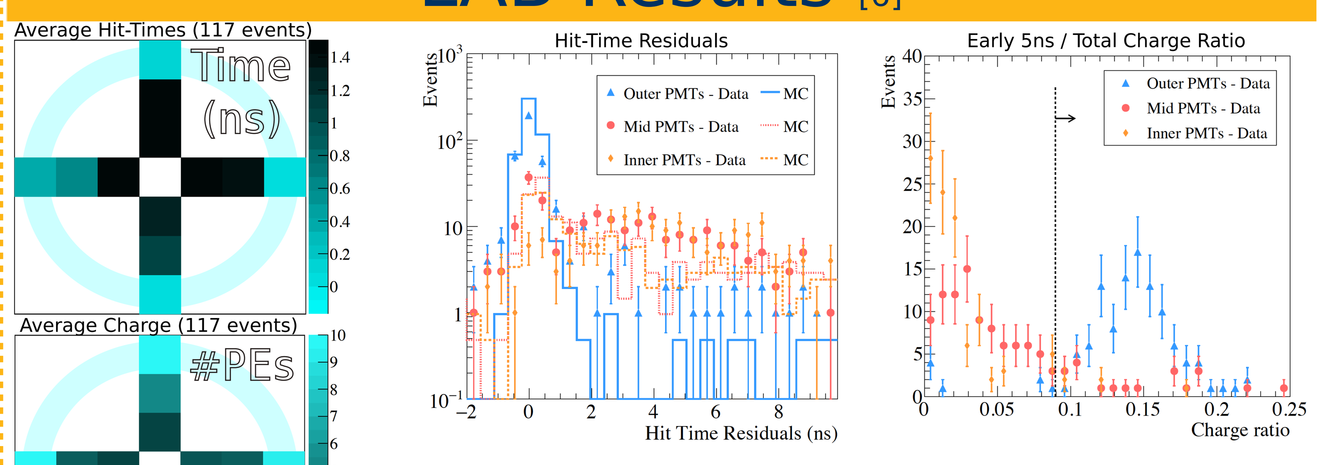




Time distribution of the first photoelectron for 135 ring candidates in water with MC comparison

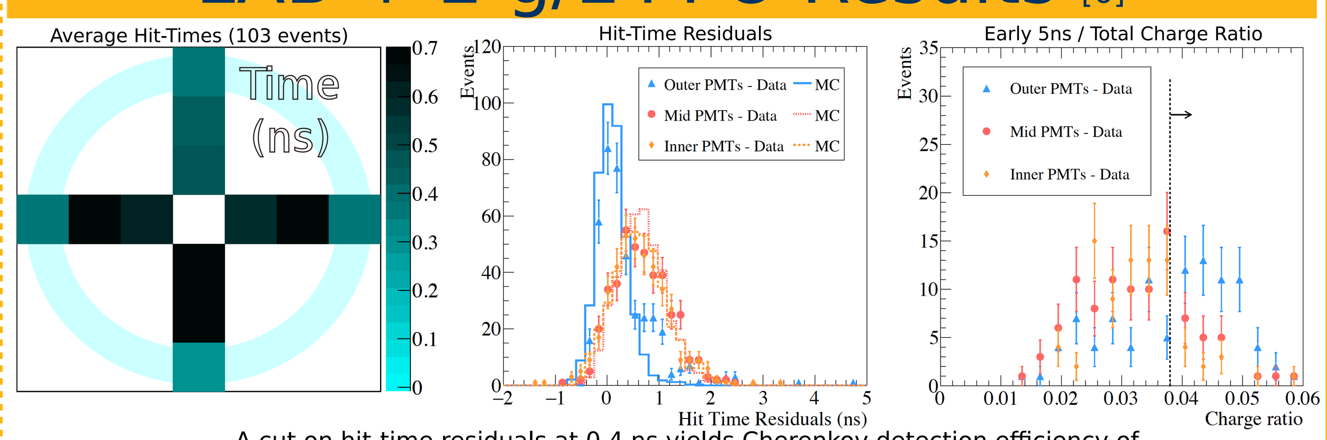
Prompt Cherenkov light from the ring candidates is used to measure the photon hit-time precision of this apparatus
338±12 ps FWHM

LAB Results [6]



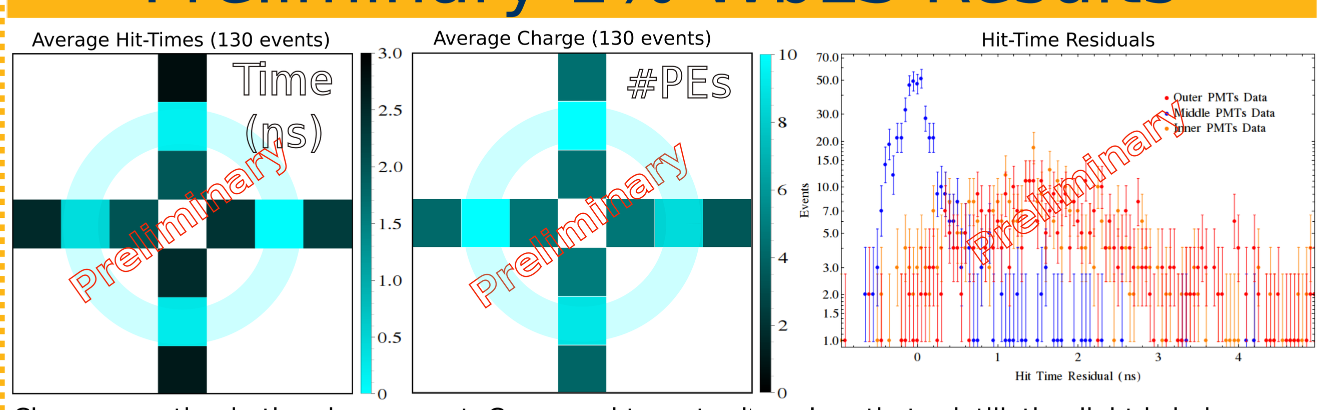
A cut on hit-time residuals at 0.4 ns yields a Cherenkov detection efficiency of 83 ± 2(stat) ± 2(syst)% with contamination of 11 ± 1(stat) ± 0(syst)%.
A threshold of Qratio = 0.09 gives a Cherenkov detection efficiency of 96 ± 2(stat) ± 0(syst)% with contamination of 6 ± 3(stat) ± 0(syst)%.

LAB + 2 g/L PPO Results [6]



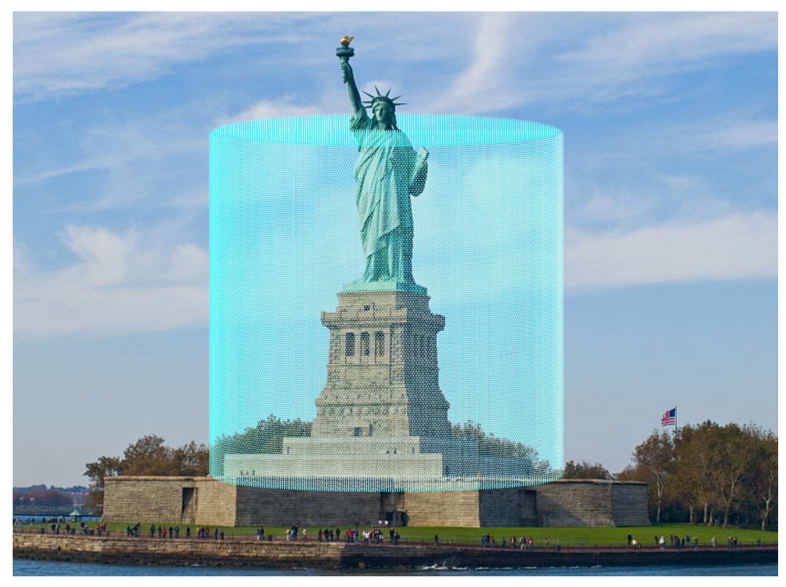
A cut on hit-time residuals at 0.4 ns yields Cherenkov detection efficiency of 70 ± 3(stat) ± 0(syst)% with contamination of 36 ± 3(stat) ± 4(syst)%.
A threshold of Qratio = 0.038 gives a Cherenkov detection efficiency of 63 ± 4(stat) ± 7(syst)% with contamination of 38 ± 3(stat) ± 2(syst)%.

Preliminary 1% WbLS Results



Clear separation in time is apparent. Compared to water it is clear that scintillation light is being seen at the 1% loading level. In charge a Cherenkov ring can be seen on top of the isotropic scintillation background. Note that with a refractive index more similar to water the Cherenkov ring falls on the middle PMTs.

A step towards THEIA



- Proposed future large scale (50kT - 100kT) WbLS neutrino detector [2][3]. The ability to separate Cherenkov and scintillation light is critical for enhancing the detector response and advancing the THEIA physics program:

Neutrinoless double beta decay
Long-baseline physics
Solar neutrinos
Nucleon decay
Geo neutrinos
Supernova neutrinos and DSNB
Sterile neutrino searches

- WbLS properties need to be well understood to optimize the THEIA design and to be able to accurately simulate events in order to model the detector response and predict the sensitivity to multiple physics goals.

ACKNOWLEDGEMENTS

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[1] M. Yeh et al., "A new water-based liquid scintillator and potential applications", Nucl. Inst. & Meth. A 66051 (2011)
[2] G.D. Orebi Gann et al., "Physics Potential of an Advanced Scintillation Detector: Introducing THEIA", arXiv:1504.08284
[3] J. R. Alonso et al., "Advanced Scintillator Detector Concept (ASDC)", arXiv:1409.5864
[4] RAT-PAC is an Analysis Tool, http://rat.readthedocs.io/en/latest/
[5] J. Caravaca et al., "An Experiment to Demonstrate Cherenkov / Scintillation Signal Separation" arXiv:1610.02029 [physics.ins-det]
[6] J. Caravaca et al., "Cherenkov and Scintillation Light Separation in Organic Liquid Scintillators" arXiv:1610.02011 [physics.ins-det]